Child Universes in the Laboratory

Stefano Ansoldi*
International Center for Relativistic Astrophysics (ICRA)
and Università degli Studi di Udine, Udine, Italy
email: ansoldi@trieste.infn.it
Eduardo I. Guendelman
Ben Gurion Univeristy, Beer Sheva, Israel
email: guendel@bgu.ac.il

November 5th, 2006

Abstract

Although cosmology is usually considered an observational science, where there is little or no space for experimentation, other approaches can (and have been) also considered. In particular, we can change rather drastically the above, more passive, observational perspective and ask the following question: could it be possible, and how, to create a universe in a laboratory? As a matter of fact, this seems to be possible, according to at least two different paradigms; both of them help to evade the consequences of singularity theorems. In this contribution we will review some of these models and we will also discuss possible extensions and generalizations, by paying a critical attention to the still open issues as, for instance, the detectability of child universes and the properties of quantum tunnelling processes.

1 The studies so far . . .

The world Cosmology stems from the Greek word *cosmos*, which meant *beauty*, *harmony*, and is the name of that branch of science which studies the origin and evolution of the universe. Thus, considering its name and the object of its study, it is, perhaps, natural to take a "passive" point of view when dealing with cosmological problems, where we use the word *passive* to emphasize that our experience of cosmology is mainly observational in nature. This may undoubtedly be a condition that seems hard to change *in practice*: after all we are dealing with problems, as the birth of our universe and its evolution in the present state, which do not appear suitable for a direct experimental approach. On the other hand, we do not see any reason why this should prevent us from changing our *attitude* toward the problem, switching from a contemplative to a more active one. In our opinion, a stimulation in this sense is coming already from the theory which first gave us the opportunity to address cosmological problems quantitatively, i.e. General Relativity. General Relativity raises for the first time the concept of causality as a central one in physics. This means that, taking a very pragmatic point of view, we have to admit that only a subset of what exists in our universe can be experienced/observed by us. This is not because of our limited capabilities as humans, but, more fundamentally, because of the restrictions imposed by the spacetime structure on the causal relations among objects. At the same time causality also brings a challenge to cosmologists in connection with the *large scale* spacetime structure; this is because the simplest models of the universe which are built according to General Relativity and whose late time predictions have a reasonable degree of consistency with what we observe, seem doomed to have an initial singularity in their past so that field equations break down exactly where we would like to set up the initial conditions. This undesirable situation looks even more disappointing after the observation that many parameters describing the state of the early universe are quite far from the domain of "very large scales" which characterizes the present observable universe. Let us, for instance, consider a Grand Unified Theory scale of 10^{14} Gev: the universe could then emerge from a classical bubble which starts from a very small size and has a mass of of the order of about 10 Kg (by using quantum tunnelling the mass of the bubble could be arbitrarily small, but the probability of production of a new universe out of it would be reduced). The density of the universe would, admittedly, have been quite higher than what we could realize with present technologies, but the orders of magnitude of the other parameters make not unreasonable to ask the question: might we have the possibility of building a child universe in the laboratory?

As a matter of fact, a positive answer to this question was already envisaged some years ago (for a popular level discussion see [28]). In particular Farhi *et al.* suggested an interesting model able to describe universe creation starting from a non-singular configuration and involving semiclassical effects. This proposal, actually, leaves some open issues, for instance about the semiclassical part of the process and the global (Euclidean) structure of the solution. Although since then, a few more proposal have appeared, addressing in more detail qualitative issues, it is interesting to observe that most of the problems which emerged in the earliest formulation are, somehow, still open. It is our hope that the present review of the different approaches which have been developed along this interesting research line, will stimulate to study in more detail and with systematic rigor these problems as well as other realistic answers to the above question. In our opinion, this question is not a purely academic one, and might help not only to change our perspective (passing from an observational to an experimental one) in addressing cosmological problems, but also to shed some light on the importance of the interplay of gravitational and quantum phenomena.

We would also like to remark how, this complementary perspective can be considered much more promising nowadays than some years ago, thanks to the results of recent observations. These observations are helping us in focusing our field of view back in time, closer and closer to the earliest stages of life of our universe and are providing us with a large amount of data and information that will, hopefully, help us in sharpen our theoretical models. This has already allowed tighter constrains on the parameters of models of the early universe, giving us the chance for a more decisive attack of most of the still open problems. This will be a great help also for a “child universe formation in the laboratory” program; it can make easier to identify the fundamental elements (building blocks) required to model the *creation* of a universe that will evolve in something similar to the present one. At the same time, it will help us to narrow our selection of the fundamental principles that forged the earliest evolution of the universe, and, as we said already before, strengthen our hope to enlighten a crucial one, which is the interplay between General Relativity and Quantum Theory.

This said, in the rest of this section, keeping in mind the above preliminary discussion, we are going to give a concise review of the state of the art in the field and to to make a closer contact with some of the models for child universe formation; in particular we are going to review some of the existing works on the dynamics of vacuum bubbles and on topological inflation (both also considered in a semiclassical framework).

Callan and Coleman initiated the study of vacuum decay more than 30 years ago [10, 9]; after their seminal papers the interest in the subject rapidly increased. The possible interplay of true vacuum bubbles with gravitation was then considered [11, 25]. More or less at the same time and as opposed with the true vacuum bubbles of Coleman *et al.*, false vacuum bubbles were also considered. The classical behavior of regions of false vacuum coupled to gravity was studied by Sato et *al.* [33, 23, 31, 27, 32, 22] and followed by the works of Blau *et al.* [7] and Berezin *et al.* [5, 6]. The analysis in [7] clarified some aspects in the study of false vacuum dynamics coupled to gravity; in it, for the first time, the problem was formulated using geodesically complete coordinate systems: this made more clear the issue of wormhole formation, with all its rich sequel of stimulating properties and consequences.

The presence of wormholes makes possible a feature of false vacuum bubbles that is otherwise counterintuitive, which is that these objects can undergo an exponential inflation without displacing the space outside of the bubble itself; this could seem strange at a first look and is due to the fact that they have an energy density which is higher than that of the surrounding spacetime and which is responsible for keeping the required pressure difference. Because of this, *child universe* solutions appear as expanding bubbles of false vacuum which disconnect from the exterior region. Apart from the already mentioned wormhole, they are also characterized by the presence of a *white-hole like* initial singularity; the simplest example can be obtained by modelling the region inside the bubble with a domain of de Sitter spacetime and the region outside the bubble with a domain of Schwarzschild spacetime. These two regions are then joined across the bubble surface, using the well known Israel junction conditions [21, 4]; Einstein equations, which hold independently in the two domains separated by the bubble, are also satisfied on the bubble surface if interpreted in a distributional sense; they determine the motion (embedding) of the bubble in the two domains of spacetime. Although there are various simple configurations of this system (as well as more elaborate generalizations) that are appropriate to describe the evolution of a newly formed universe (i.e. they are such that the expanding bubble can become very large), these *classical* models present also some undesirable features. In particular it turns out that only bubbles with masses above some critical value can expand from very small size to infinity. But then these solutions necessarily have a (white-hole) singularity in their past; in fact, for all of them the hypotheses of singularity theorems are satisfied.

In connection with the restriction on the values of the total mass, the situation could be improved in theories containing an appropriate multiplet of additional scalars[19][1]: then all bubbles that start evolving from zero radius can inflate to infinity if the scalars are in a "hedgehog" configuration, or global monopole of big enough strength. This effect also holds in the gauged case for magnetic monopoles with large enough magnetic charge: in this way the mass requirement is traded for requirements about the properties of magnetic monopoles.

A possible connection of this approach with the problem of the initial singularity appears, then, from the work of Borde *et al.* [8]: they proposed a mechanism which, by means of the coalescence of two regular magnetic monopoles (with *below critical* magnetic charge), is able to produce a *supercritical* one, which then inflates giving rise to a child universe. This idea might help addressing the singularity problem and in this context it is very interesting the work of Sakai *et al.* [30]: in it the interaction of a magnetic monopole with a collapsing surrounding membrane is considered; also in this case a new universe can be created and the presence of an initial singularity *in the causal past of the newly formed universe* can be avoided.

To solve the problem of initial singularity, there are also other approaches which make a good use of quantum effects. Needless to say, these ideas are very suggestive because they require a proper interplay of quantum and gravitational physics, for which a consistent general framework is still missing. This is the main reason why most of these investigations try to obtain a simplified description of the system by requiring a high degree of symmetry from the very beginning. In particular, if we describe the bubble separating the inflating spacetime domain from the surrounding spacetime in terms of Israel junction conditions [21, 4], under the additional assumption of spherical symmetry, the dynamics of the system is determined by the dynamics of an effective system with only one degree of freedom: this is called the *minisuperspace approximation*; in this framework the problem of the semiclassical quantization of the system, even in the absence of an underlying quantum gravity theory, can be undertaken with less (but still formidable) technical problems using as a direct guideline the semiclassical procedure with which we are familiar in ordinary Quantum Mechanics. This has been the seminal idea of Farhi *et al.* [12] and of Fishler *et al.* [14, 13]. One additional difficulty in these approaches was in connection with the stability of the classical initial state. Interestingly enough, this could

[1]The subject of inflation assisted by topological defects was also studied later in [35] and [26].

be solved by the introduction of massless scalars or gauge fields that live on the shell and produce a classical stabilization effect of false vacuum bubbles. By quantum tunnelling, these bubbles can then become child universes [15] and, at least in a $2+1$-dimensional example [18], it has been shown that the tunnelling can be arbitrarily small.

2 ... and their future perspectives

From the above discussion, we think it is already clear that there are many interesting aspects in the study of models for child universe creation in the laboratory. We would also like to remember how most of these models are based on a very well-known and studied classical system, usually known as a *general relativistic shell* [21, 4]. The classical dynamics of this system is thus "under control", many analytical results can be found in the literature and numerical methods have also been employed (see the introduction of [1] for additional references). On the other hand there has been little progress in the development of the quantized theory, which still remains a non-systematized research field. We stress how a progress in this direction would be decisive for a more detailed analysis of the semiclassical process of universe creation.

Before coming back to the quantum side of the problem, let us first consider what could be done on the classical one. We will concentrate mainly on the works of Borde *et al.* [8] and of Sakai *et al.* [30], which suggest many interesting ideas for further developments. For instance, it is certainly important to extend the analysis in [8], which is mainly qualitative in nature, to take fully into account the highly non-linear details of the collision process by means of which a supercritical monopole is created (this is certainly instrumental for a quantitatively meaningful use of the idea of topological inflation). Also the study performed in [30] should be extended; to obtain some definitive conclusion about the stability of the initial configuration, it is, in fact, necessary to study the spacetime structure of the model for all possible values of the parameters; it could then be possible to determine if stability is a general feature of monopole models or an *accident* of some particular configurations. From the classical point of view, in both the above models another central point is the study of their causal structure; it can be obtained by well-known techniques, but, again, a full classification of all the possibilities that can arise is certainly required to gain support for the proposed mechanisms. Known subtleties which require closer scrutiny (as for example, the presence of singularities in the causal past of the created universe *but* not in the past of the experimenter creating the universe in the laboratory or, sometimes, the presence of timelike *naked* singularities) make a discussion of the problem of initial conditions not only interesting but necessary, especially in this context[2].

A suggestive complement to the classical aspects discussed above, is represented, of course, by the quantum (more precisely semiclassical) ones, where

[2]The proper analysis of the Cauchy problem will, in fact, involve resolution or proper handling of these singularities.

quantum effects are advocated to realize the tunnelling between classical solutions. If (i) the classical solution used to describe the initial state can be formed without an initial singularity and is stable, (ii) the classical solution which represents the final state can describe an inflating universe and (iii) we can master properly the tunnelling process, then we could use the quantum creation of an inflating universe *via* quantum tunnelling to evade the consequences of singularity theorems. The construction of proper initial and final states has already been successfully accomplished. The stability of the initial classical configuration has been, instead, only partly analyzed [15] and it would be certainly interesting to consider the tunnelling process in more general situations, where, for example, the stabilization can be still classical in origin. Although there is some evidence [30] of a general way to solve this issue in the context of monopole configurations, as we mentioned above, the analysis should be extended to the whole of the parameter space. At the same time a complementary possibility is that *semiclassical* effects might stabilize the initial configuration. In particular, closely related to the problem of instabilities present in many models, is the fact that the spacetime surrounding the vacuum bubble has itself an instability due to presence of a white hole region (see, for instance, [34]). Also in this context quantum effects might stabilize the system and help solving the issue. This approach could require the determination of the stationary states of the system in the WKB approximation, a problem for which a generalization of the procedure presented in [1] (where this analysis was performed for the first time in a simplified model) could be useful.

Another equally (if not more) important point for future investigations is certainly related with the still open issues in the semiclassical tunnelling procedure. We will shortly discuss this by following, for definiteness, the clear, but non-conclusive, analysis developed by Farhi *et al.* [12]: it is shown in their paper that, when considering the tunnelling process, it is not possible to devise a clear procedure to build the manifold interpolating between the initial and final classical configurations; this manifold would describe the instanton that is assumed to mediate the process. According to the discussion of Farhi *et al.* it seems possible to build only what they call a *pseudo-manifold*, i.e. a manifold in which various points have multiple covering. To make sense of this, they are forced to introduce a 'covering space' different from the standard spacetime manifold, in which they allow for a change of sign of the volume of integration required for the calculation of the tunnelling action and thus of tunnelling probabilities. It would be important to put on a more solid basis this interesting proposal, comparing it with other approaches which might help to give a more precise definition of this *pseudo-manifold*. In particular we would like to mention two possibilities. A first one uses the *two measures theory* [16]; considering four scalar fields it is possible to define an integration measure in the action from the determinant of the mapping between these scalar fields and the four spacetime coordinates; there can, of course, be configurations where this mapping is not of maximal rank and if we then interpret the scalar fields as coordinates in the *pseudo-manifold* of [12], then the non-Riemannian volume element of the two measures theory would be related to the non-Riemannian structure that could be associated to the *pseudo-manifold*. In this perspective, non-Riemannian volume elements could be essential to make sense of the quantum creation of a universe in the laboratory and it could be important to develop the theory of shell dynamics in the framework described by the two measures theory.

A second one, likely complementary, can come from a closer study of the Hamiltonian dynamics of the system. Let us preliminarily remember that the Hamiltonian for a general relativistic shell, which we are using as a model for the universe creation process, is a non quadratic function of the momentum (this comes from the non-linearities intrinsic to General Relativity); this makes the quantization procedure non-standard and quite subtle too. Moreover, although it is possible to determine an expression for the Euclidean momentum and use it to reproduce [2] standard results for the decay of vacuum bubbles (as for instance the results of Coleman *et al.* [11]) this momentum can have unusual properties along the tunnelling trajectory; some of these inconsistencies disappear if we consider the momentum as a function valued on the circle instead than on the real line [3] but further investigations in this direction are required; they will likely help us to obtain a better understanding of the semiclassical tunnelling creation of this general relativistic system and, perhaps, show us some interesting properties of the interplay between the quantum and the gravitational realms. In this context, it should be also explored how the Euclidean baby universes [29] could be matched continuously to the real time universes and in this way provide new ways to achieve spontaneous creation of real time baby universes

To complement the above discussion, we would now like to provide some additional contact points between theoretical ideas and experimental evidence. We start considering if all *creation efforts* might end in a child universe totally disconnected from its *creator* or not. Of course, there is not a definitive answer also to this problem yet, since this is tightly bound to the child universe creation model. Nevertheless, it it is certainly stimulating to address the question if, in some way, the new universe might be detectable. There is an indication in this direction from the analysis performed in [24]: here a junction with a Vaidya radiating metric is employed, so that the child universe could be detectable because of modifications to the Hawking radiation. Generalizations that apply to solitonic inspired universe creation[3] can be important, especially from the point of view of a quantum-gravitational scenario in which the exact and definite character of classical causal relations might be *waved* by quantum effects.

Other issues that could be tackled after having a more detailed model of child universe creation, are certainly phenomenological ones. They would also help to better understand the differences between purely classical and partly quantum processes, which is also a motivation to consider them explicitly and separately. Also the physical consequences of different values of the initial parameters characterizing the child universe formation process (initial conditions) should be analyzed[4] and in this context we would also like to recall the idea of

[3]It is, for instance, certainly possible to extend the metric describing the monopole, i.e. the Reißner-Nordström spacetime, to the Reißner-Nordström-Vaidya case.

[4]In particular different ways of creating a universe in the laboratory could lead to different

Zee *et. al* [20], i.e. that a creator of a universe could pass a message to the future inhabitants of the created universe. From our point of view this is can be a suggestive way to represent the problem of both initial conditions and causal structure; this could be of relevance also for the problem of defining probabilities in the context of the multiverse theory and of eternal inflation.

A final point of phenomenological relevance would be in connection with observations that suggest the universe as super-accelerating. This seems to support the idea that some very unusual physics could be governing the universe, in the sense that standard energy conditions might not be satisfied. In the context of child universes creation in the laboratory in the absence of an initial singularity, it might very well be that a generalized behavior of the universe to try to raise its vacuum energy would manifest itself locally with the creation of bubbles of false vacuum (as seen by the surrounding spacetime), which would then led to child universes. In [17] a proposal, based on the two measures theory, to avoid initial singularities in a homogeneous cosmology has already been put forward. It would then be desirable to apply it to the non-singular child universe creation also.

To conclude we cannot miss to point out how all the above discussion about the possibility of producing child universes in the laboratory could take a completely new and concrete perspective in connection with the possible existence of new physics at the TeV scale in theories with large compact extra-dimensions, physics that might become available to our experimental testing at the colliders which will shortly start to operate.

Acknowledgements

We would like to thank H. Ishihara and J. Portnoy for conversations.

References

[1] S. Ansoldi, "WKB metastable quantum states of a de Sitter-Reissner-Nordstroem dust shell", *Class. Quantum Grav.*, 19:6321–6344, 2002.

[2] S. Ansoldi, A. Aurilia, R. Balbinot and E. Spallucci, "Classical and quantum shell dynamics, and vacuum decay", *Class. Quantum Grav.*, 14:2727-2755, 1997.

[3] S. Ansoldi and L. Sindoni, "Gravitational tunnelling of relativistic shells", Proceedings of the Sixths international Symposium of Frontiers in Fundamental Physics, Università degli Studi di Udine, Springer 2006.

[4] C. Barrabes and W. Israel, "Thin shells in general relativity and cosmology: the lightlike limit", *Phys. Rev. D*, 43:1129–1142, 1991.

coupling constants, gauge groups, etc..

[5] V. A. Berezin, V. A. Kuzmin, and I. I. Tkachev, “Dynamics of bubbles in general relativity”, *Phys. Rev. D*, 36:2919, 1987.

[6] V. A. Berezin, V. A. Kuzmin, and I. I. Tkachev, “Black holes initiate false-vacuum decay”, *Phys. Rev. D*, 43:R3112–R3116, 1991.

[7] S. K. Blau, E. I. Guendelman, and A. H. Guth, “Dynamics of false vacuum bubbles”, *Phys. Rev. D*, 35:1747, 1987.

[8] A. Borde, M. Trodden, and T. Vachaspati, “Creation and structure of baby universes in monopole collisions”, *Phys. Rev. D*, 59:043513, 1999.

[9] C. G. Callan Jr. and S. Coleman, “Fate of the false vacuum. II. First quantum corrections”, *Phys. Rev. D*, 16:1762–1768, 1977.

[10] S. Coleman, “Fate of the false vacuum: Semiclassical theory”, *Phys. Rev. D*, 15:2929–2936, 1977.

[11] S. Coleman and F. De Luccia, “Gravitational effects on and of vacuum decay”, *Phys. Rev. D*, 21:3305–3315, 1980.

[12] E. Farhi, A. H. Guth, and J. Guven, “Is it possible to create a universe in the laboratory by quantum tunneling?”, *Nucl. Phys. B*, 339:417–490, 1990.

[13] W. Fischler, D. Morgan, and J. Polchinski, “Quantization of false vacuum bubbles: a hamiltonian treatment of gravitational tunneling”, *Phys. Rev. D*, 42:4042–4055, 1990.

[14] W. Fishler, D. Morgan, and J. Polchinski, “Quantum mechanics of false vacuum bubbles”, *Phys. Rev. D*, 41:2638–2641, 1990.

[15] E. I. Guendelman and J. Portnoy, “The universe out of an elementary particle?”, *Class. Quantum Grav.*, 16:3315–3320, 1999.

[16] E. I. Guendelman and A. B. Kaganovich, “Dynamical measure and field theory models free of the cosmological constant problem”, *Phys. Rev. D*, 60:065004, 1999.

[17] E. I. Guendelman and A. B. Kaganovich, “Fine tuning free paradigm of two measures field theory: k-essence, inevitable dynamical protection from initial singularity and inflation with graceful exit to $\Lambda = 0$ state”, *gr-qc/0607111*, pages 1–35, 2006.

[18] E. I. Guendelman and J. Portnoy, “Almost classical creation of a universe”, *Mod. Phys. Lett. A*, 16:1079–1087, 2001.

[19] E. I. Guendelman and A. Rabinowitz, “Gravitational field of a hedgehog and the evolution of vacuum bubbles”, *Phys. Rev. D*, 44:3152, 1991.

[20] S. Hsu and A. Zee, “Message in the sky”, *Mod. Phys. Lett.A* 21:1495–1500, 2006.

[21] W. Israel, "Singular hypersurfaces and thin shells in general relativity", *Nuovo Cimento*, B44:1, 1966; (errata: *Nuovo Cimento*, B48:463, 1967).

[22] H. Kodama, M. Sasaki, and K. Sato, "Abundance of primordial holes produced by cosmological 1st-order phase transition", *Progr. Theor. Phys.*, 68:1979–1998, 1982.

[23] H. Kodama, M. Sasaki, K. Sato, and K. Maeda, "Fate of wormholes created by 1st order phase-transiitons in the early universe", *Progr. Theor. Phys.*, 66:2052–2072, 1981.

[24] K. M. Larsen and R. L. Mallet, "Radiation and false vacuum bubble dynamics", *Phys. Rev. D*, 44:333, 1991.

[25] K. Lee and E. J. Weinberg, "Decay of true vacuum in curved spacetime", *Phys. Rev. D*, 36:1088–1094, 1987.

[26] A. Linde, "Monopoles as big as a universe", *Phys. Lett. B*, 327:208–213, 1994.

[27] K. Maeda, K. Sato, M. Sasaki, and H. Kodama, "Creation of Schwarzschild-de Sitter wormholes by a cosmological first-order phase transition", *Phys. Lett. B*, 108:98–102, 1982.

[28] Z. Merali, "Create your own universe", *New Scientist*, 2559:32–35, 2006.

[29] H. B. Nielsen and M. Ninomiya, "Baby universe theory", Proc. of *3rd Regional Conf. on Mathematical Physics*, Islamabad, Pakistan, Feb 18-24, 1989

[30] N. Sakai, K. Nakao, H. Ishihara, and M. Kobayashi, "The universe out of a monopole in the laboratory?", *Phys. Rev. D*, 74:024026, 2006.

[31] K. Sato, "Production of magnetized black-hole and wormholes by 1st-order phase transitions in the early universe", *Progr. Theor. Phys.*, 66:2287–2290, 1981.

[32] K. Sato, H. Kodama, M. Sasaki, and K. Maeda, "Multi-production of universes by first-order phase transition of a vacuum", *Phys. Lett. B*, 108:103–107, 1982.

[33] K. Sato, M. Sasaki, H. Kodama, and K. Maeda, "Creation of wormholes by 1st order phase-transiton of a vacuum in the early universe", *Progr. Theor. Phys.*, 65:1443–1446, 1981.

[34] F. J. Tipler, "Horizon stability in asymptotically flat spacetimes", *Phys. Rev. D*, 16:3359–3368, 1977.

[35] A. Vilenkin, "Topological inflation", *Phys. Rev. Lett.*, 44:3137–3140, 1994.